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14. ABSTRACT
The Frozen Rock Experiment (FRE) was conducted in central Alaska in August 2006 to provide empirical data on seismically-estimated yield from explosions in frozen rock. Laboratory studies have demonstrated that frozen rock is significantly stronger than unfrozen rock, and it has been hypothesized that this increased strength, due to ice in the pores and cracks, can alter seismic yield. Central Alaska has abrupt lateral boundaries in discontinuous permafrost, and we detonated 3 shots in frozen, saturated rock and 3 shots nearby in unfrozen, dry rock ranging in size from 200 to 350 lbs. Approximately 125 accelerometers and seismometers were deployed specifically for this experiment at distances of 10 m to over 20 km. During the past year, we have conducted various studies (moment tensors, magnitudes, etc.) to characterize the explosions in frozen and unfrozen rock. In order to conduct moment tensor inversions, a velocity and an attenuation model are required. We initially developed a 1-D model for central Alaska but found that the model could not account for azimuthally dependent velocities and did not explain observed surface-wave arrival times. We are currently developing a 3-D "block" velocity model using full waveform modeling in order to improve the preliminary moment tensor results. To develop an attenuation model for the upper crust of central Alaska, spectral amplitudes of Rg were extracted from complex waveforms using phase match filtering. The Rg amplitudes were then corrected for geometric spreading and regressed against distance to determine the attenuation coefficients at each period, which were then converted to QRg using the group velocity dispersion curves. We developed the relationship $QRg(f) = 12.5f^{-0.39}$. When the attenuation coefficient data were inverted, Q values of less than 20 were required in the upper kilometer of the central Alaskan crust. To model the sources, the *in-situ* *P*- and *S*-wave velocities of the frozen and unfrozen rock test sites were input into the Mueller-Murphy (MM; 1971) source model. The resulting source models predict that the explosions at the faster, frozen rock site should have a higher corner frequency (fc~15 Hz) than an equivalent explosion at the slower, unfrozen site (fc~10.5 Hz). MM also predicts a small overshoot to the explosions at the frozen rock site. Examinations of the observed spectra from the explosions match both the fc and overshoot predictions. The MM model predicts that the frozen-rock explosions should have slightly larger amplitudes at frequencies less than fc; however, the observed data show that the amplitudes are approximately equivalent in this bandwidth. Denny and Johnson (1991) was used to predict Mws for the explosions, and the resulting values closely matched the observed Mws obtained from surface wave spectral amplitude modeling. Our results show that MM and Denny and Johnson (1991) source theories do an excellent job of modeling these small explosions when the *in-situ* *P*- and *S*-wave velocities of frozen and unfrozen rock are considered.

15. SUBJECT TERMS
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EXPLOSION SOURCE CHARACTERISTICS IN FROZEN AND UNFROZEN ROCK

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Weston Geophysical Corp.[1] and New England Research, Inc.[2]

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ABSTRACT

The Frozen Rock Experiment (FRE) was conducted in central Alaska in August 2006 to provide empirical data on seismically-estimated yield from explosions in frozen rock. Laboratory studies have demonstrated that frozen rock is significantly stronger than unfrozen rock, and it has been hypothesized that this increased strength, due to ice in the pores and cracks, can alter seismic yield. Central Alaska has abrupt lateral boundaries in discontinuous permafrost, and we detonated 3 shots in frozen, saturated rock and 3 shots nearby in unfrozen, dry rock ranging in size from 200 to 350 lbs. Approximately 125 accelerometers and seismometers were deployed specifically for this experiment at distances of 10 m to over 20 km. During the past year, we have conducted various studies (moment tensors, magnitudes, etc.) to characterize the explosions in frozen and unfrozen rock.

In order to conduct moment tensor inversions, a velocity and an attenuation model are required. We initially developed a 1-D model for central Alaska but found that the model could not account for azimuthally dependent velocities and did not explain observed surface-wave arrival times. We are currently developing a 3-D "block" velocity model using full waveform modeling in order to improve the preliminary moment tensor results. To develop an attenuation model for the upper crust of central Alaska, spectral amplitudes of *Rg* were extracted from complex waveforms using phase match filtering. The *Rg* amplitudes were then corrected for geometric spreading and regressed against distance to determine the attenuation coefficients at each period, which were then converted to Q_{Rg} using the group velocity dispersion curves. We developed the relationship $Q_{Rg}(f) = 12.5f^{-0.39}$. When the attenuation coefficient data were inverted, Q values of less than 20 were required in the upper kilometer of the central Alaskan crust.

To model the sources, the *in-situ P*- and *S*-wave velocities of the frozen and unfrozen rock test sites were input into the Mueller-Murphy (MM; 1971) source model. The resulting source models predict that the explosions at the faster, frozen rock site should have a higher corner frequency (f_c~15 Hz) than an equivalent explosion at the slower, unfrozen site (f_c~10.5 Hz). MM also predicts a small overshoot to the explosions at the frozen rock site. Examinations of the observed spectra from the explosions match both the f_c and overshoot predictions. The MM model predicts that the frozen-rock explosions should have slightly larger amplitudes at frequencies less than f_c; however, the observed data show that the amplitudes are approximately equivalent in this bandwidth. Denny and Johnson (1991) was used to predict M_ws for the explosions, and the resulting values closely matched the observed M_ws obtained from surface wave spectral amplitude modeling. Our results show that MM and Denny and Johnson (1991) source theories do an excellent job of modeling these small explosions when the *in-situ P*- and *S*-wave velocities of frozen and unfrozen rock are considered.

The *laboratory-determined P*- and *S*-wave velocities of the frozen and unfrozen rock test sites were used in the MM source model; however, the predicted corner frequencies were much higher than the observed data. The lab velocities are more indicative of deeper emplacement depths where there are fewer fractures and where any effect of the ice is predominantly-porosity related. We modeled a 1 kiloton explosion at a depth of 122 meters using the lab-determined velocities for frozen and unfrozen saturated rocks and found less than a 0.05 magnitude unit (m.u.) difference in their M_ws (unfrozen had larger M_w), which agrees with Rautian and Khalturin (2003), who observed less than 0.1 m.u. difference for explosions in the former Soviet Union in frozen and unfrozen media.

OBJECTIVES

The consortium of Weston Geophysical, New England Research, and the University of Alaska, Fairbanks, conducted the Frozen Rock Experiments (FRE) in central Alaska to characterize the variations in ground motion scaling and coupling for explosions in frozen and unfrozen rock. We recorded the explosions on arrays of near-source and local stations deployed specifically for the experiment. The results are being interpreted to help understand possible biases in the estimation of seismic yield from explosions in frozen rock.

RESEARCH ACCOMPLISHED

Experiment Background

A critically important aspect of nuclear test monitoring is yield estimation. United States monitoring agencies must be able to accurately estimate yields for nuclear explosions detonated in regions of monitoring concern. If frozen-rock emplacement conditions create a circumstance favorable for biased yields, data must be available such that any bias can be accounted for when the yield is estimated. Prior studies (Mellor, 1971) have established that frozen-rock properties are considerably different from unfrozen-rock properties. Moreover, it has been hypothesized that these altered properties may be sufficient to cause significant variations in seismic coupling, which in turn, significantly alters seismic yield estimates.

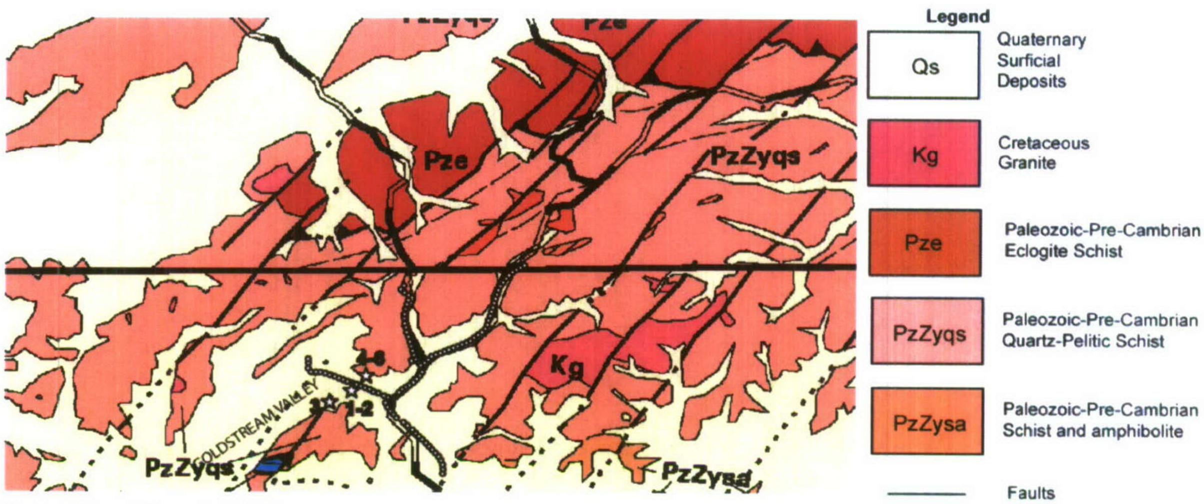
Sammis and Biegel (2004) noted that an increase in low-temperature uniaxial strength is related to the ice in the initial pores and cracks. The ice increases the apparent coefficient of sliding friction on these initial cracks. Since the strengthening is strain-rate dependent, for nuclear explosions the full strengthening should occur in a small range near 0 °C. Increasing the seismic velocity and/or rock strength would cause reduced seismic amplitudes in the far-field for explosions in frozen rock, which would result in an underestimated yield.

Experimental Setting

The objective of our project was to conduct nearly co-located explosions in frozen and unfrozen crystalline rock. To find a possible location for the experiment, we consulted the permafrost map of Alaska (Ferrians, 1965) for regions of discontinuous permafrost. One such location with frozen and unfrozen rock was a gold mine located 25 km north of Fairbanks, Alaska; however, test boreholes at this location proved that there was less than a 0.2°C difference between the unfrozen and frozen test sites (e.g., -0.1°C and +0.1°C, respectively). Discussions with property owners, miners, and drillers familiar with the ice stratigraphy in the region suggested that better sites with larger temperature contrasts were available for our study. One site that a local landowner proposed was in the Goldstream Valley, which is approximately 10 km north of Fairbanks, near the town of Fox, Alaska.

Gold was first discovered in the Fairbanks area in 1902 in the northern extents of Goldstream Valley. As a result, much of the Quaternary gravels and surficial deposits (Figure 1) that comprise the valley floor have been reworked with dredges through placer mining. One section that had not been dredged previously was an active gold mine with a working face that offered a cross-section of the geology in the valley floor. The top layer consisted of 5 meters of organic-rich, fine-grained glacial silt that had massive ground ice. This was followed by 5 meters of frozen gravels that overlie Paleozoic/Precambrian-aged quartz-pelitic schist, which the mine operators insisted was frozen based on how hard it was to "rip" for placer gold mining. The valley floor and mine pit are behind the shadow cast by the south rim of the valley for much of the year, allowing virgin ground to remain frozen and the reworked dredge piles to often refreeze. The gravels and frozen rocks in the valley grade into unfrozen, dry bedrock on its northern rim. Because this is a south-facing hill that receives plenty of sunlight throughout the year, it is not frozen. This is typical for this region of discontinuous permafrost in interior Alaska, where south-facing hills are unfrozen while north-facing slopes and valleys are typically frozen.

Thermal Characterization in Goldstream Valley. Test boreholes were drilled to a depth of 10 meters at the proposed frozen and unfrozen rock explosion sites. Each borehole was filled with 1.5-inch-diameter PVC pipe capped on both ends, backfilled with drill cuttings, and allowed to thermally equilibrate for 5–7 days. Vladimir Romanovsky at the University of Alaska, Fairbanks, installed thermistors in each hole allowing the temperatures to be measured at 1-meter depth intervals.



Geologic Map: Wilson *et al.*, 1998.

Figure 1. Geologic map of the Frozen Rock Experiment test sites. The white stars show the location of the small explosions in frozen (1–3) and unfrozen (4–6) rock. Small white circles positioned on the roads near the test site represent geophones deployed to record the experiment (Map from Wilson et al., 1998).

With the exception of seasonal thawing in the top meter, the proposed frozen test site (Shots 1–2) is below freezing, approaching a temperature of -1.35°C at the depth of explosives emplacement (approximately 8 meters). At the unfrozen test site, the rocks are above freezing at all depths in the borehole with a temperature at emplacement depth of +2.34°C. The relative differences between the temperatures at the frozen and unfrozen sites were larger, and the magnitude of the frozen-rock temperature colder than other sites we had examined during the experiment planning. Additionally, ice was visible in the fractures of the frozen rock at this location.

Laboratory Velocity Analysis. Rock samples from the test sites were sent to New England Research, Inc., for analysis. The physical rock properties of each sample were measured both saturated and dry at room temperature, and then the measurements were performed again when the samples were chilled to below -8 °C. Seismic velocities obtained from the laboratory analysis are presented in Figure 2.

Due to an unmapped metamorphic facies change between the two test sites, there are compositional differences in core samples taken from each test site as observed in thin section analyses (Figure 3). The rocks both have the same quartz, plagioclase, and mica matrix, which is foliated by the metamorphism. The grade of metamorphism is different with the unfrozen test site rock being schistose, while the frozen test site bedrock was gneissic (as will be so referenced for the rest of this paper). The difference in composition between the two samples are the large garnets observed in the unfrozen test site sample while only smaller garnets are observed in the frozen-rock sample.

Laboratory velocity analyses of these rocks (Figure 2) show that the differences in the mineral composition do not cause significant changes in the *P*- and *S*-wave velocities of the two samples. When the core samples from both test sites are saturated and cooled to -8°C, the *P*-wave velocity for the unfrozen test site sample—with large garnets—is approximately 0.1 km/s faster (e.g., 5.8 vs. 5.7 km/s) than the frozen test site sample at a wide range of confining pressures. At room temperature, the *P*-wave velocities for both saturated samples are similar (e.g., 5.4 vs. 5.2 km/s). Given that the unfrozen test site was dry, we also estimated the laboratory *P*- and *S*-wave velocities of a dry, unfrozen schistose sample, which was considerably slower at 4.1 and 2.8 km/s, respectively. All of these velocities are compiled in Table 1.

***In Situ* Velocity Analysis.** We conducted shallow geophysical investigations of both test sites. We used a 60-channel Geometrics system connected to a *P*-wave source recorded on three-component Mark-4 geophones. We picked the first breaks and inverted them for velocity structure for each test site. At the frozen test site, for which the working mine pit offers visual confirmation of the stratigraphy, we resolved the frozen gravel, which is highly

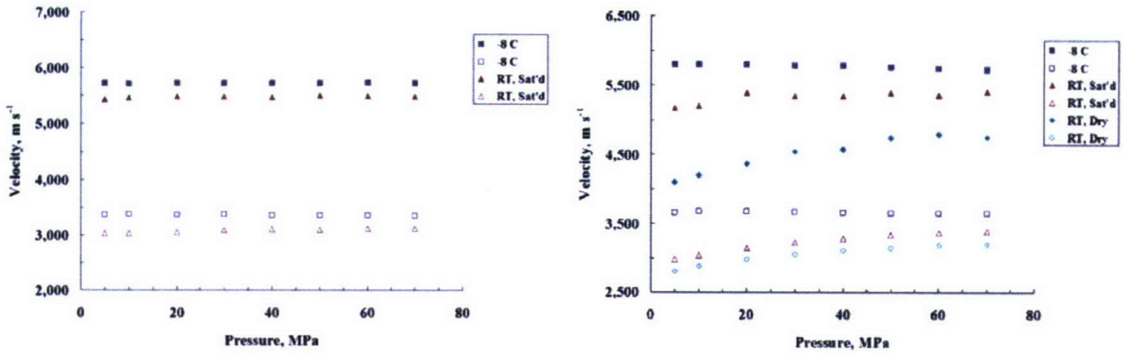
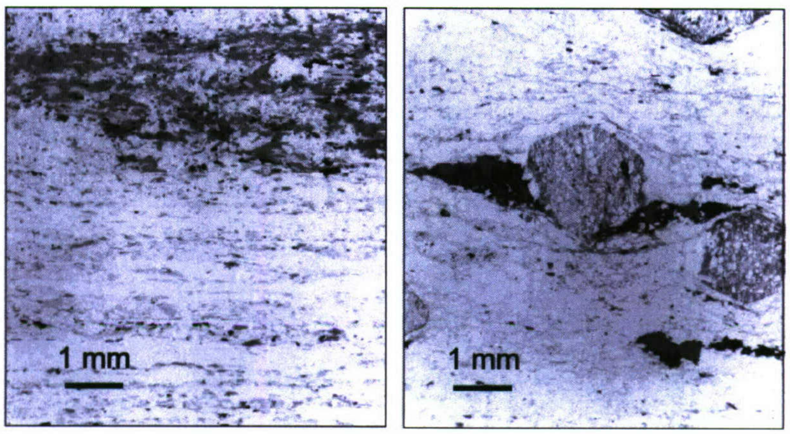


Figure 2. ***P*- and *S*-wave velocity estimates when the frozen test site rock sample (left) and unfrozen test site rock sample (right) were frozen (-8°C) and unfrozen (RT) in laboratory settings. Because the second test site was dry, we also include the lab-based velocities of the rock when unsaturated.**

a) Frozen Test Site Sample | a) Unfrozen Test Site Sample



Frozen Test Site Sample	Unfrozen Test Site Sample
Quartz-Plagioclase	Quartz-Plagioclase
Biotite-Muscovite-Chlorite	Muscovite
Garnet-Sphene	Almandine Garnet
Chlorite	Chlorite-Sericite
Fe-S-Oxides	Opaques

Figure 3. Photomicrographs of core samples from the (a) frozen and (b) unfrozen rock test sites with the mineralogical constituents.

Table 1. Summary of Seismic Velocities for the Emplacement Media

Media	Laboratory		*In Situ*	
	V_p	V_s	V_p	V_s
Gneiss: Frozen	5.7	3.3	3.7	1.6
Gneiss: Unfrozen	5.4	3.0		
Schist: Frozen	5.7	3.6		
Schist: Unfrozen	5.2	3.0		
Schist: Unfrozen and Dry	4.1	2.8	2.0-2.6	1.0-1.2

variable with *P*-wave velocities ranging from 1.6–2.5 km/s, and the fast bedrock (3.7 km/s). At the unfrozen test site, the dry bedrock *P*-wave velocity is only 2–2.6 km/s, and there was a velocity change near the middle of the explosives column with slower velocities above the bedrock. While drilling the boreholes at the unfrozen test site, we observed abrupt changes in the penetration rate at similar depths to our inverted interfaces.

We did not have direct *S*-wave refraction data, thus we attempted to invert the ground roll dispersion curves for each test site. The frozen test site shear-wave velocity is considerably faster than the unfrozen test site, with ground roll velocities ranging from 1.18 to 1.8 km/sec. The dispersion observed at the unfrozen test site is relatively flat and only ranges between 0.82 and 1.19 km/sec. Inversion of these dispersion curves (Herrmann, 2008) provided estimates of the shear-wave velocities at the depth of explosion emplacement of 1.6 km/sec and 1.0–1.2 km/sec for the frozen and unfrozen test sites, respectively.

Explosion Detonation

We detonated 6 explosions at the Goldstream Valley test sites on 24–26 August 2006. The yields ranged from 100 to 359 lbs of ammonium nitrate fuel oil (ANFO) explosives. Shots 1 (200 lbs), 2 (350), and 4 (200), 5 (350), and 6 (100) were all detonated in 10-meter boreholes loaded with at least 5 meters of stemming. Shot 3 (359) was detonated in a 15 meter borehole in frozen gravels. Because the event was the last shot on the first day, for safety reasons, we eliminated all unused boosters resulting in the increased yield as compared to Shots 2 and 5.

Explosion Source Modeling

Figure 4 provides an interesting snapshot of the differences in seismic waves produced by explosions in frozen-saturated and unfrozen-dry rock. The paths from the sources to this station at an epicentral distance of 22 km are essentially the same; thus the factor of 3 difference in the observed amplitudes is most likely related to coupling effects in the emplacement media. We note that the smaller amplitudes for the unfrozen shots were contrary to the expected result. The theory had suggested that the increased strength of the frozen-rock media would create smaller amplitudes on the seismic phases. The questions we had to answer were whether the observed differences were related to frozen vs. unfrozen effects and/or frozen vs. unfrozen-dry effects.

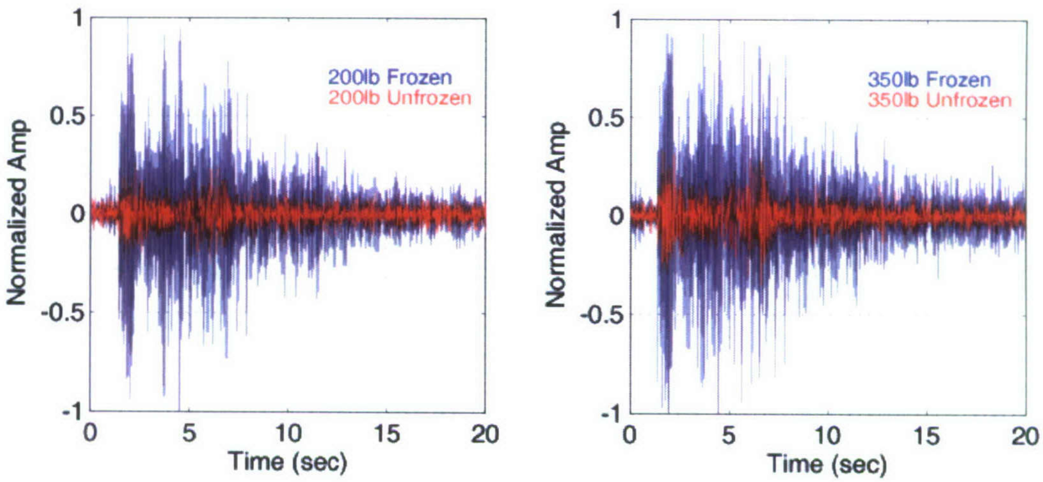


Figure 4. Seismic waves from explosions in frozen and unfrozen rock recorded at a distance of 22 km from the explosions.

To answer these questions, we attempted to model the observed spectra for the frozen and unfrozen test-site shots using the Mueller and Murphy (1971; MM71) explosion source model. MM71 was empirically developed based on nuclear explosions at the Nevada Test Site (NTS). It has been successfully applied to nuclear explosions at other test sites, mining explosions (Yang, 1997), and confined chemical explosions (Stump et al., 1999; Stump et al., 2003; Hooper et al., 2006). For our first attempt, we generated MM71 explosion-source spectra using the laboratory

velocities estimated from core samples (Table 1). The corner frequencies estimated for our small explosions with these fast laboratory velocities (e.g., $P > 4.1$ km/s and $S > 2.8$ km/s) were greater than 20–30 Hz for both test sites and did not offer a match to our observed data.

Next, we incorporated our in situ *P*- and *S*-wave velocities into the MM71 source and observed an improved correlation between the observed and theoretical spectra at near-source distances (Figure 5). The resulting source models predict that the explosions at the faster, frozen rock site should have a higher corner frequency (f_c~15 Hz) than an equivalent explosion at the slower, unfrozen site (f_c~10.5 Hz). MM71 also predicts a small overshoot to the explosions at the frozen-rock site. Examinations of the observed spectra from the explosions match the f_c and overshoot predictions, although the predicted amplitude of the overshoot is smaller than observed. The MM71 model predicts that the frozen rock explosions should have slightly larger amplitudes at frequencies of less than f_c; however, the observed data show that the amplitudes are approximately equivalent in this bandwidth.

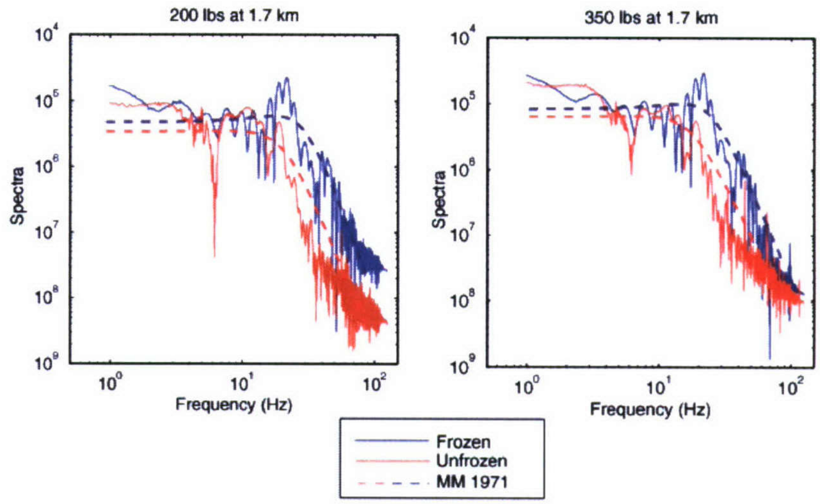


Figure 5. Comparison of observed spectra (at 1.7 km) from explosions in frozen (blue) and unfrozen-dry (red) rock. Also shown are predicted MM71 reduced-velocity potential (RVP) spectra modeled from the *in situ* velocities at each test site.

Remaining Questions

What if the unfrozen test site had been saturated? We were unable to locate a saturated and unfrozen test site in hard rock within 20 km of our frozen, hard-rock site; thus an experimentally-confirmed answer to this question is unavailable at this time. Given how well the MM71 spectra modeled the observed data, we attempted to simulate the velocities at the unfrozen test site as if it had it been saturated. To do so, we enlisted the help of an excellent resource from Tatyana Rautian and Vitaly I. Khalturin entitled "Permafrost and Seismic Efficiency of Explosions," which was handed to us at the 2008 Seismological Society of America meeting by Dr. Paul Richards. It is a wonderful reference concerning frozen rock, including permafrost depths in the former Soviet Union, a summary of laboratory studies of frozen rock, aspects of explosive coupling, and attenuation in frozen media. It was compiled in 2003.

One of the studies highlighted in Rautian and Khalturin (2003) was by Dzhurik (1983), who studied the *in situ* seismic velocities in frozen and unfrozen hard rock (metamorphic and igneous) in East Siberia. Dzhurik used a hammer drop and geophones with far offsets of 200 meters to study *P*-and *S*-wave velocities in the upper 10 meters (appropriate for our test site). Using hundreds of measurements, Dzhurik was able to develop V_p/V_s relationships for frozen-saturated, unfrozen-saturated, and dry-unfrozen rock (Figure 6). We plotted our two datapoints on Dzhurik's results, and then used the relationship for unfrozen- saturated rock (V_p=1.7+1.06V_s) to predict a range of possible velocities for our test site, had it been saturated. This interpretation is obviously no substitute for empirical explosion data; however, it may provide us with information to determine the feasibility of returning to Alaska for explosions in saturated-unfrozen rock

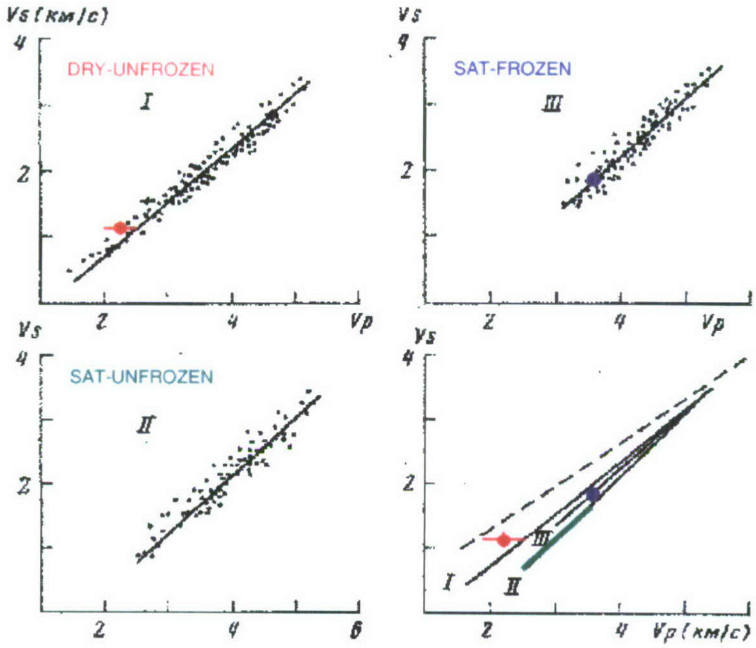


Figure 6. V_p/V_s ratios for frozen and unfrozen rock in Siberia (from Dzhurik, 1983). We plotted the *in situ* velocities of our test sites on these empirical relationships. We then used the linear relationship for II between our two data points to estimate the effect of saturation on our unfrozen test site (green line in lower-right subplot).

Figure 7 shows the MM71 source RVP spectra for our two different test sites. Also shown are a series of predicted—based on the work of Dzhurik—RVP spectra, assuming that the unfrozen test site had been saturated. These RVP spectra suggest that saturated and unfrozen rock could have produced larger amplitude signals at frequencies below the corner frequency.

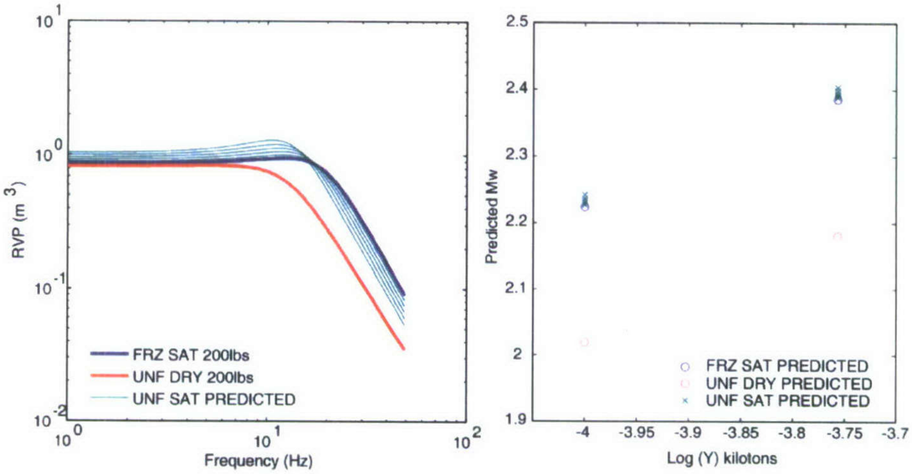


Figure 7. (Left) RVP spectra for the frozen (blue) and unfrozen-dry (red) test site explosions in the Goldstream Valley. Also shown are possible RVP spectra, assuming the relationships of Dzhurik (1983) for unfrozen-saturated rock (green). (Right) Predicted moments (Denny and Johnson, 1991) for explosions in the various media.

Denny and Johnson (1991) developed a model for the measured seismic moment (M_o) of explosions,

$$M_o = \frac{1}{311} M_t P_o^{0.3490} 10^{-0.0269GP}, \qquad (1)$$

where GP is gas porosity and P_o is overburden pressure ($P_o=\rho gh$). M_t is the theoretical moment and is defined as

$$M_t = \frac{4}{3}\pi\rho\alpha^2 R_c^3, \qquad (2)$$

where α is the P-wave velocity and R_c is the cavity radius estimated by:

$$R_c = \frac{1.47x10^4 Y^{\frac{1}{3}}}{\beta^{0.3848} P_o^{0.2625} 10^{0.0025GP}}. \qquad (3)$$

From the equations above, we can see that the measured moment for explosions in the Denny and Johnson (1991) model depends on the P-wave and S-wave (β) velocities and yield (Y). We used Equations 1–3 to estimate moment magnitudes (M_w) for the frozen and unfrozen rock explosions in Goldstream Valley. We then compared them to the moments obtained from spectral modeling of the surface wave amplitudes and found an almost 1:1 relationship between predicted and observed M_w. When the same techniques were applied to the possible saturated and unfrozen test site velocities from Dzhurik's (1983) data, the M_ws are not as large as expected (Figure 7; right). The M_w would have probably been less than 0.1 magnitude unit larger had the unfrozen test site been saturated.

How would this translate to a 1 kiloton explosion? It is beyond the scope of this project to try and predict the differences between a nuclear and chemical explosion in terms of the non-linear reactions and changes of state in frozen media. However, our successes with MM71 at modeling the near-source small explosion data could provide a valid framework to predict the spectra and moments for larger explosions (e.g., 1 kiloton at 122 meters depth) in permafrost. Since a larger explosion is likely to be buried deeper in less-fractured media, the laboratory velocities determined by New England Research (Table 1) were input in MM71 to model the emplacement media. The resulting reduced displacement potentials (RDP) for all five possible laboratory velocity combinations in Table 1 are presented in Figure 8. We see similar relative positioning of the potentials for frozen and unfrozen media as observed for the *in situ* velocities (Figures 5 and 7).

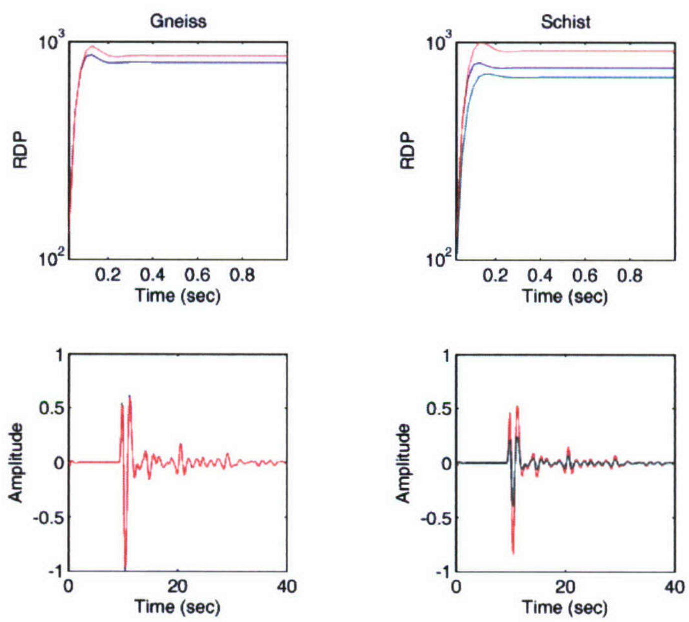


Figure 8. (Top) Reduced displacement potentials (RDP) for a 1 kiloton explosion at 122-m depth for all five possible laboratory *P*- and *S*-wave velocity combinations in Table 1. (Bottom) Synthetic seismograms resulting from the convolution of the RDPs with teleseismic explosion Green's functions generated by Robert Herrmann's new Hudson96 program.

Dr. Robert Herrmann generated teleseismic explosion Green's functions using his new Hudson96 modeling software (Herrmann, 2008) that were convolved with the RDPs in Figure 8 to produce synthetic seismograms. We then estimated M_ws using Denny and Johnson (1991) and m_bs using the synthetic *P*-wave amplitudes and

$$m_b = \log(A/T) + Q(D, h), \qquad (4).$$

where Q (D, h) was obtained from the Veith-Clawson (1972) curves. The results presented in Figure 9 predict very small differences in magnitudes for frozen and unfrozen saturated rock explosions based on the MM71 model and laboratory velocities for gneiss and schist.

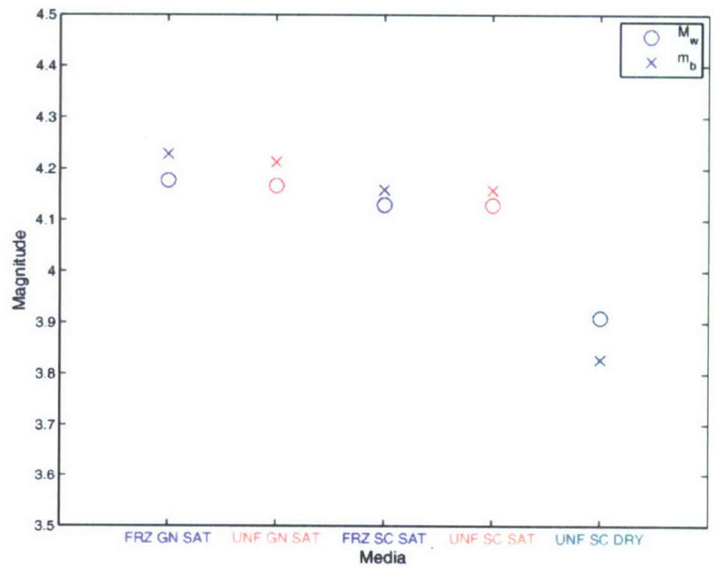


Figure 9. Predicted M_w and m_b magnitudes for a 1 kiloton explosion in frozen and unfrozen gneiss (GN) and schist (SC) based on the MM71 source and teleseismic explosion Green's functions.

How do our results compare with Rautian and Khalturin? Our results suggest that there may not be significant magnitude variations between explosions detonated in frozen and unfrozen gneiss and schist as long as both are saturated. Rautian and Khalturin (2003) also attempted to address the possible coupling differences between explosions in frozen and unfrozen rock. First, they studied 23 Peaceful Nuclear Explosions (PNEs) that were detonated in permafrost regions. These included 8 in permafrost and 15 at depths below the base of the permafrost. They determined that the PNEs detonated in permafrost were about 0.1 magnitude unit larger than the shots below the permafrost. After considering the effects of depth, they report that "these data evidenced, that anyway, the permafrost does not affect seriously on magnitude effectiveness."

They also studied the nuclear explosions at Novaya Zemlya, but offered the surprising conclusion that most of the underground nuclear tests there were detonated deeper than the base of the permafrost. They determined that magnitude deviations between shots in and below the permafrost varied only between -0.01 and +0.04. They wrote, "so, again, there is no notable difference in magnitude efficiency, caused by permafrost."

Rautian and Khalturin (2003) also studied attenuation in frozen rocks as a possible source of amplitude bias. They concluded that the "frozen state of rock approximates its properties (velocities, moduli, strength) to that of hard rock (granite or so). It means, there is no reason to expect the high energy loss if the non-linear attenuation zone is in permafrost."

CONCLUSIONS AND RECOMMENDATIONS

The Frozen Rock Experiment provides a unique dataset from small, nearly co-located explosions in frozen and unfrozen metamorphic rocks for which we have detailed laboratory and *in situ* characterizations of the emplacement

media. The characteristics of the explosions (corner frequency, overshoot, and isotropic moments) are modeled very well using the in situ velocity characteristics of the emplacement media and both the Mueller and Murphy (1971) and Denny and Johnson (1991) source models. The primary reason behind the differences in the explosions is related to the dry versus saturated-frozen emplacement media. Using Dzhurik's (1983) relationships between V_p and V_s for Siberian hard rock media, we predict a very small increase in amplitudes from the unfrozen-rock explosions had the media been saturated as compared to the frozen-rock explosions. Incorporating the laboratory velocities of our test site media into the Mueller-Murphy source, we predict little or no m_b bias for explosive coupling in frozen and unfrozen media—unless the unfrozen media is dry. These results agree with Rautian and Khalturin (2003) who found no "notable" difference in magnitude efficiency for explosions detonated in permafrost.

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REFERENCES

Denny, M. D. and L. R. Johnson (1991). The explosion seismic source function: model and scaling laws revisited, in H. J. Patton and P. G. Richards, Eds., Explosion Source Phenomenology, *Geophysics Monograph* 65, American Geophysical Union, Washington, pp 1–24.

Dzhurik, V. I. (1983). Issledovaniye uprugikh parametrov talykh i merzlych skal'nykh gruntov, *Inzhenernaya Geologiya* 1983(3): 45–54.

Ferrians, O. J, (1965). Permafrost map of Alaska: U.S Geological Survey Miscellaneous, *Geologic Investigations* Map I-445.

Herrmann, R. B. (2008). Computer Programs in Seismology software. St. Louis University.

Hooper, H., J. Bonner, and M. Leidig, (2006). Effects of confinement on short-period surface waves: observations from a new dataset. *Bull. Seism. Soc. Am.* 96: 697–712.

Mellor, M. (1971). Strength and deformability of rocks at low temperatures, Hanover, NH, Cold Regions Research and Engineering Laboratory (CRREL), U. S. Army Corps of Engineers, Research Report 294.

Mueller, R. A., and J. R. Murphy (1971). Seismic characteristics of underground nuclear detonations: Part I, Seismic scaling law of underground detonations, *Bull Seism. Soc. Am.* 61: 1675.

Rautian, T. G. and V. I. Khalturin (2003). Permafrost and seismic efficiency of explosions.

Sammis, C. and R. Biegel (2004). Mechanics of strengthening in crystalline rock at low temperatures: a preliminary assessment, in *Proceedings of the 26th Seismic Research Review: Trends in Nuclear Explosion Monitoring*, LA-UR-04-5801, Vol. 2, pp. 475–484.

Stump, B. W., D. C. Pearson, and R. E. Reinke, (1999). Source comparisons between nuclear and chemical explosions detonated at Rainier Mesa, Nevada Test Site. *Bull. Seism. Soc. Am.* 89: 409–422.

Stump, B. W., D.C. Pearson, and V. Hsu, (2003). Source scaling of contained chemical explosions as constrained by regional seismograms. *Bull. Seism. Soc. Am.* 93: 1212–1225.

Veith, K. F., and G. E. Clawson (1972). Magnitude from short-period *P*-wave data, *Bull. Seism. Soc. Am.* 62: 435–452.

Wilson, F.H., J. H. Dover, D. C. Bradley, F. R. Weber, T. K. Bundtzen, and P. J. Haeussler (1998). Geologic Map of Central (Interior) Alaska. *U.S. Geological Survey Open-File Report OF 98-133-A*: http://pubs.usgs.gov/of/1998/of98-133-a/

Yang, X., (1997). Mining explosion and collapse source characterization and modeling with near-source seismic data. Ph.D. Thesis, Southern Methodist University, Dallas, Texas.